High-Speed Transient Sensing Using Dielectric Micro-Resonators

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1. Research objective

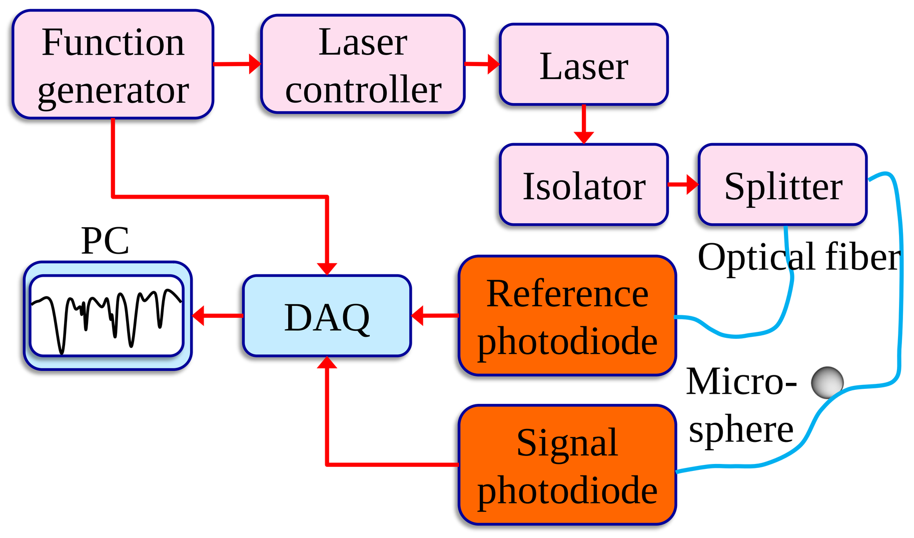
- Use whispering gallery mode (WGM) phenomenon for high bandwidth transient sensing

2. Approach

- Tune laser diode with harmonic waveform
- Develop a dynamic calibration approach
- Use high-speed data analysis methods to track WGM shifts
- Carry out proof-of-concept experiments to validate new high-speed sensing approach

3. Opto-electronics setup

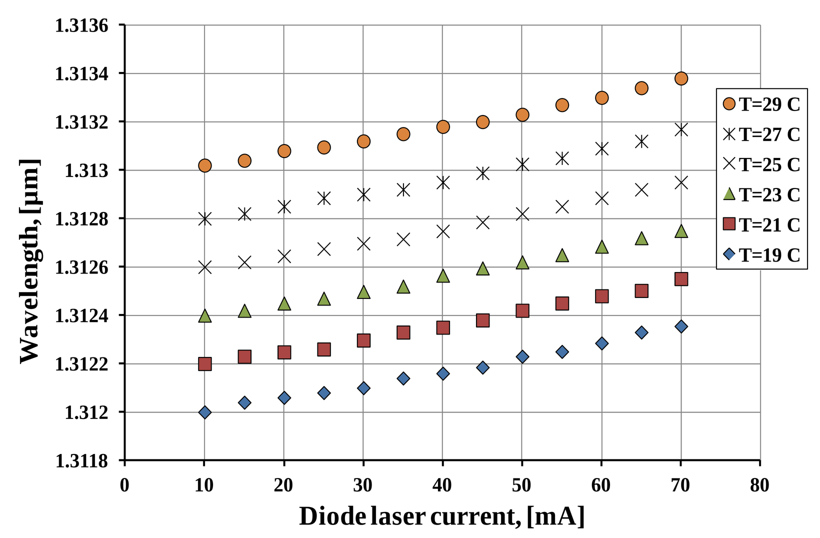
A tunable distributed feedback laser (DFB) with nominal wavelength of ~1312 nm and 10 mW maximum power drives the sensor system.



Schematic of the opto-electronic setup

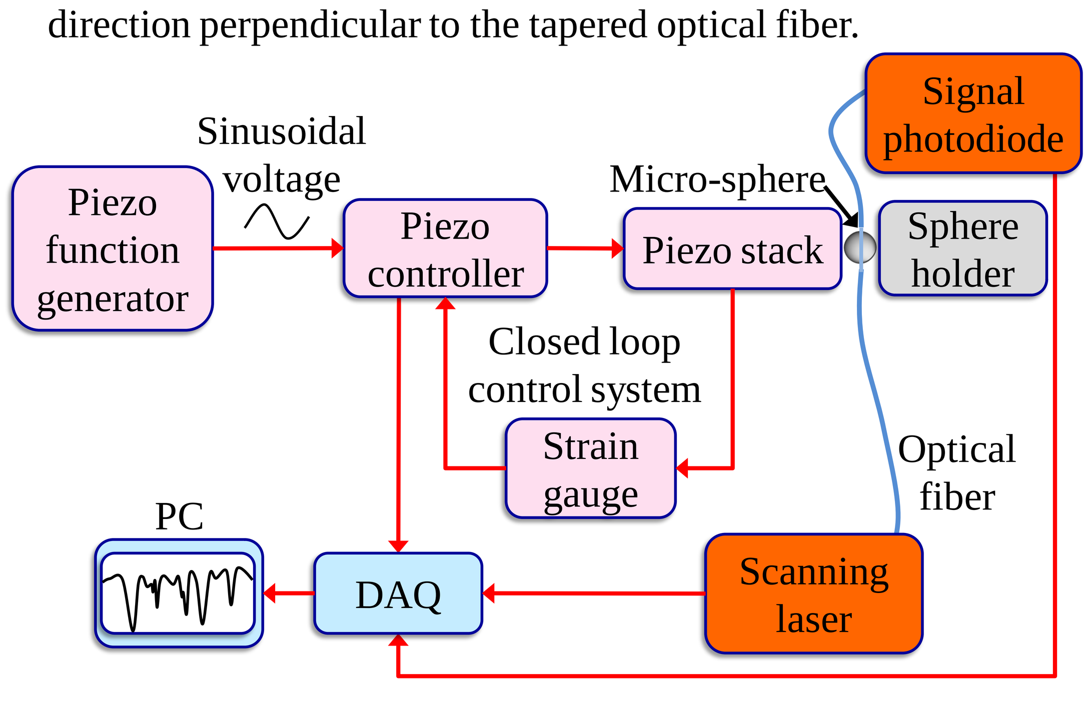
4. Laser calibration

In a typical application [1,2], the laser wavelength is calibrated statically by slowly varying the temperature or input current and monitoring its output using a laser wave-meter. The figure below shows current-tuned calibration curves for a DFB laser at several temperatures. There is strong temperature dependence of the laser wavelength. For example, 0.1 °C change in the laser temperature induces a wavelength shift of ~ 0.01nm.

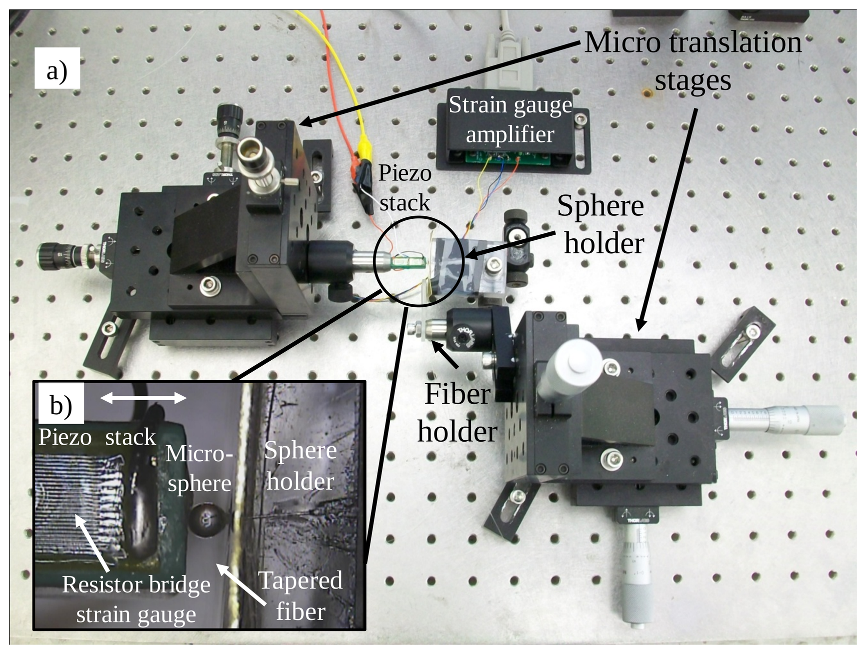


Static calibration curves for the DFB laser

Force is exerted on the micro-resonator by using two hardened steel pads that compress the micro-resonator in the direction perpendicular to the tapered optical fiber.

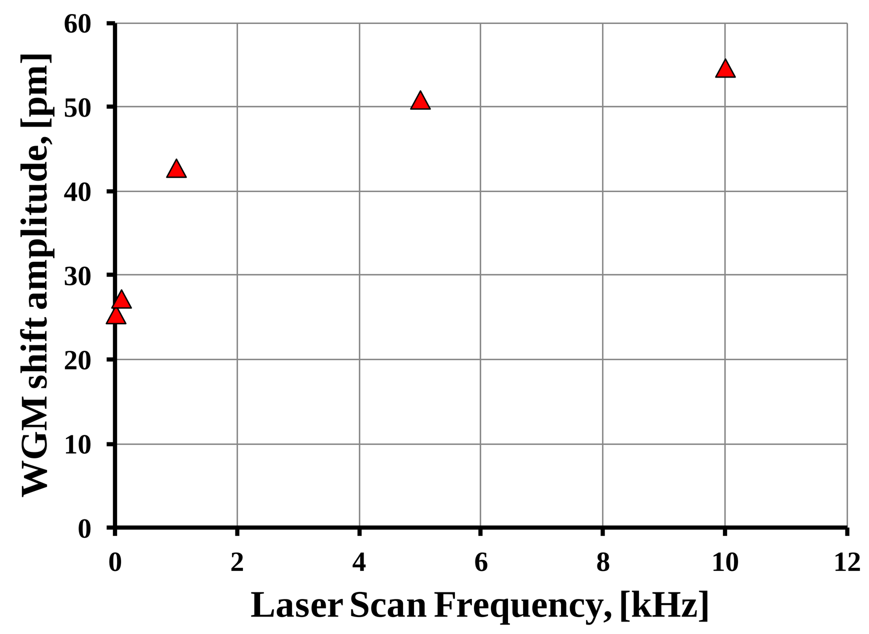


Opto-electronic setup for force experiment



Photograph of ; a) The force experimental setup, b) The close-up to the micro-resonator compressed by a piezo stack

The figure below shows the WGM shift amplitudes observed at laser tuning frequencies ranging between 1 Hz and 10 kHz. Although the compression force amplitude (hence, sphere deformation) is the same for all the measurements, larger WGM shifts are registered with increasing laser tuning frequency, leading to significant measurement errors. The larger the scanning speed, the smaller laser wavelength's tuning range. We tune the laser using a harmonic rather than a ramp waveform to eliminate thermal inertia induced waveform distortions and properly account for tuning range reductions at high scan frequencies.



WGM shift dependency on laser scan frequency

5. Analysis

Using a lumped-heat capacity thermal model the laser's tuning behavior in terms of its temperature, T, can be expressed as follows:

$$\rho c V \frac{dT}{dt} = \dot{Q}\,Sin(\omega t) + \dot{Q}_o - \beta\,(T - T_\infty) \qquad (1)$$

Here, ρ, c and V are the density, specific heat and volume of the laser crystal, respectively. $\dot{Q}_o$ is the DC power supplied to the laser while $\dot{Q}$ is the amplitude of the harmonic power input providing the tuning at frequency, ω and $\dot{Q}_o \geq \dot{Q}$. The last term on the right hand side of equation (1) describes the laser cooling where β is the cooling coefficient and T_∞ is the ambient temperature (assumed constant). Substituting $T_o = T - T_\infty$ and $\Lambda = \rho c V$ in equation (1) we have

$$\Lambda \frac{dT_o}{dt} = \dot{Q}\,Sin(\omega t) + \dot{Q}_o - \beta(T_o) \qquad (2)$$

The general solution of (2) is

$$T_o(t) = Ce^{\frac{-\beta t}{\Lambda}} + \frac{\dot{Q}\left[\beta\,Sin(\omega t) - \Lambda\omega\,Cos(\omega t)\right]}{\beta^2 + \omega^2\Lambda^2} + \frac{\dot{Q}_o}{\beta} \qquad (3)$$

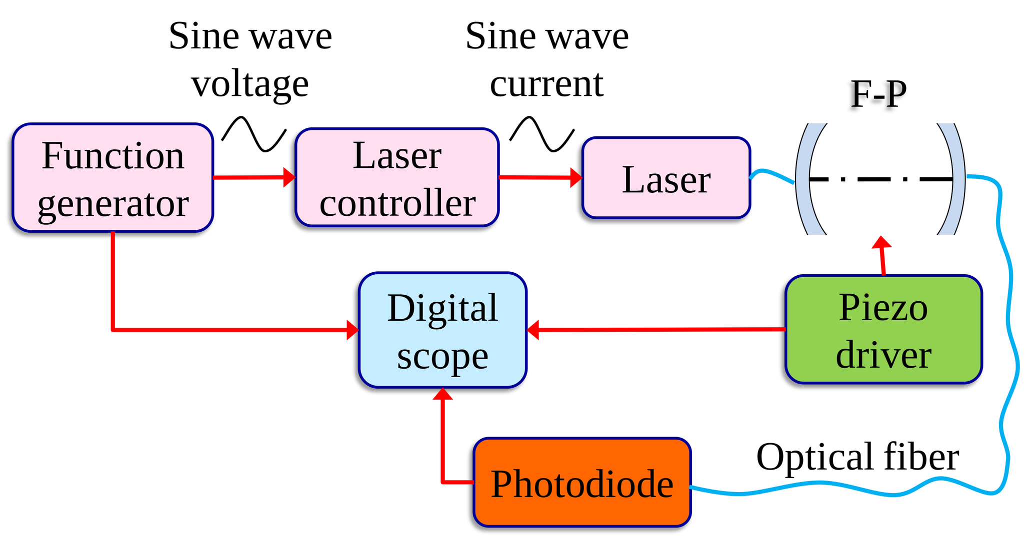
where, C is a constant defined by the initial temperature. The first term on the right hand side represents the transient response. Therefore, assuming the tuning of the laser is achieved solely by the thermal effect the harmonic tuning of the laser can be expressed by

$$\lambda(t)\ \alpha\ \frac{\dot{Q}\left[\beta\,Sin(\omega t) + \Lambda\omega\,Sin\left(\omega t - \frac{\pi}{2}\right)\right]}{\beta^2 + \omega^2\Lambda^2} \qquad (4)$$

Equation (4) provides a relationship between the laser input power and its output wavelength and demonstrates the strong dependence of the wavelength on scanning frequency. It indicates smaller tuning amplitudes and larger phase delays at larger scan frequencies, ω, with a maximum phase delay of $\pi/2$.

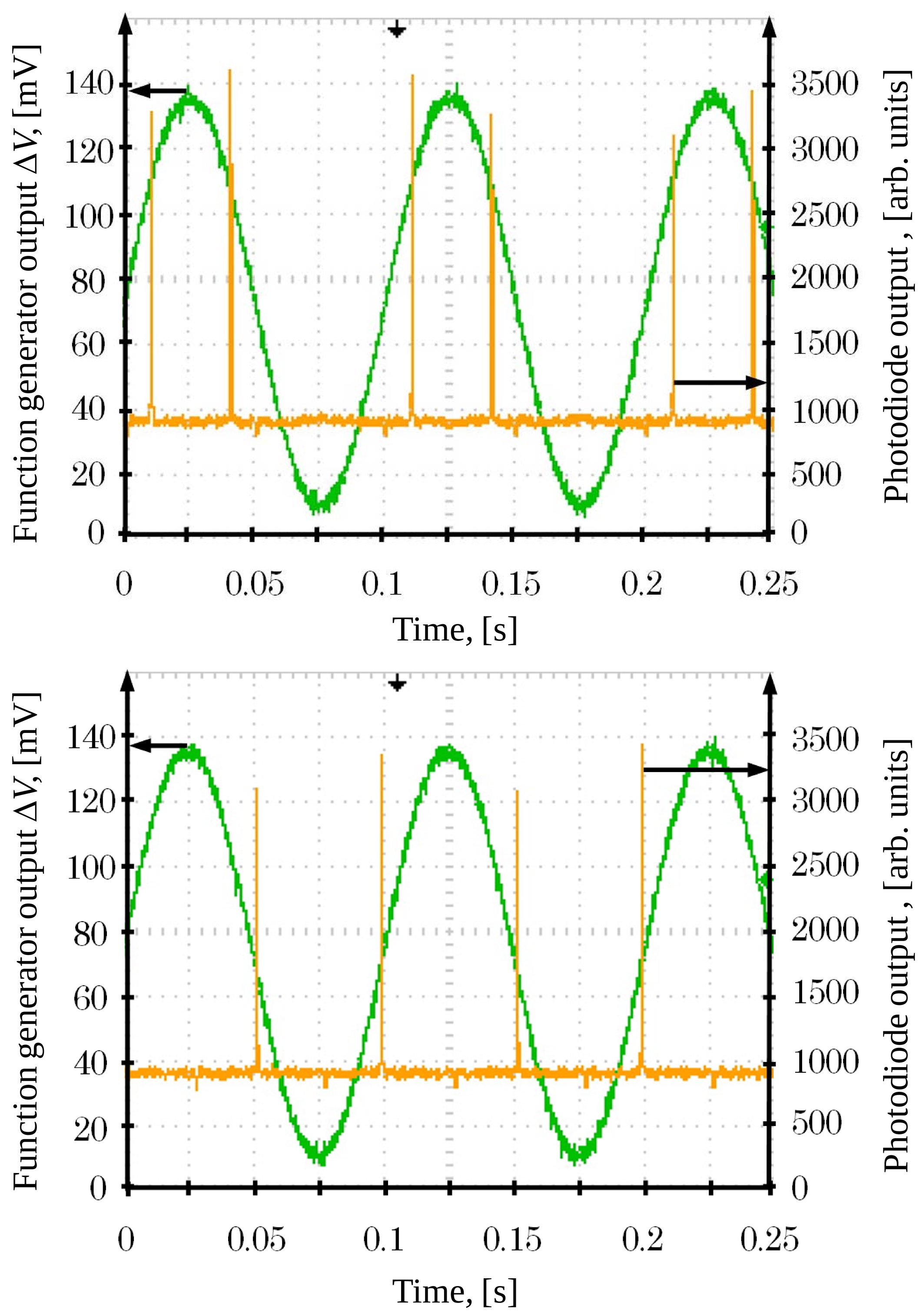
6. Dynamic calibration of laser

We tune the DFB laser using a harmonic waveform and calibrate the laser output at various scanning frequencies, ω, and amplitudes using a Fabry-Perot interferometer. The figure below shows a block diagram of the opto-electronic setup used in the calibrations. The laser scanning frequency ranged between 1 Hz and 10 kHz.



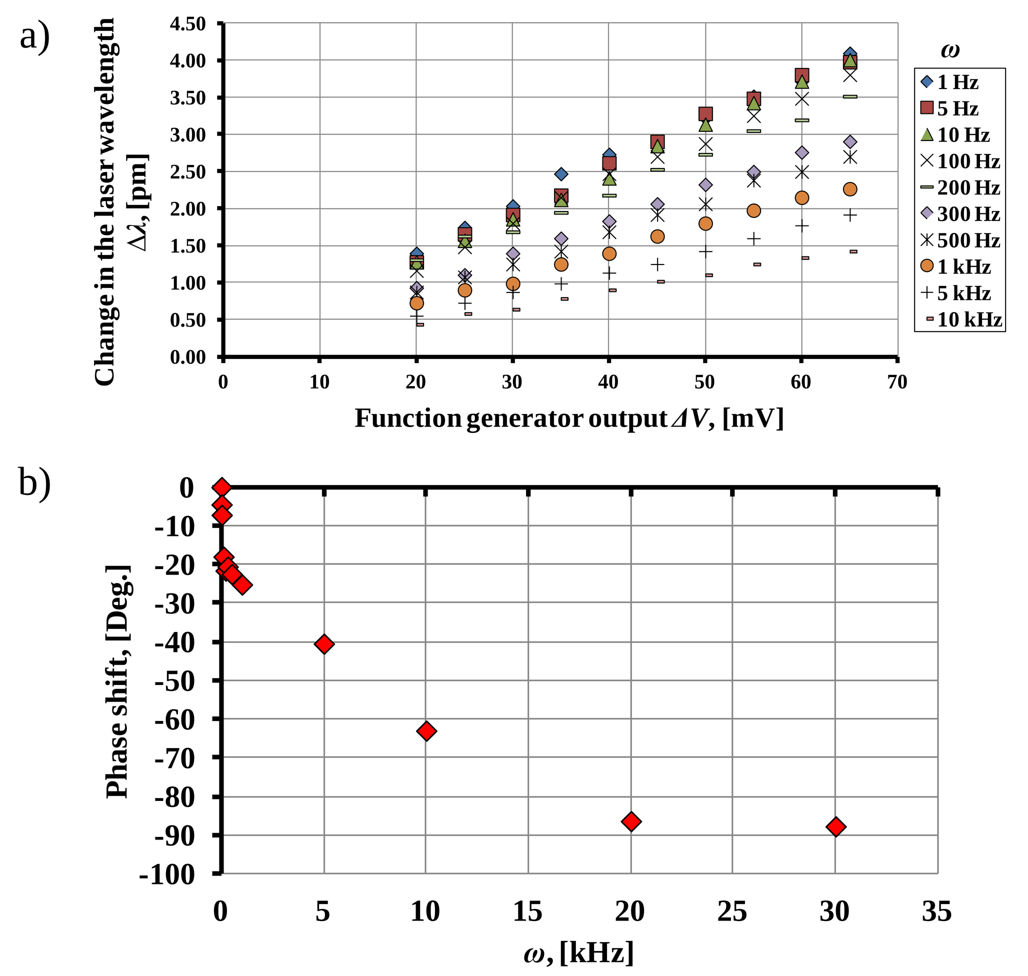
Schematic of the calibration setup

The dynamic calibration procedure of the laser using a Fabry-Perot interferometer is indicated in the figure below where the oscilloscope traces of the function generator output and photodiode signal are shown for two F-P cavity settings (wavelength change of $\Delta\lambda$ = 3.98 pm) for a laser scan frequency of ω = 10Hz



Oscilloscope trace of function generator and photodiode outputs for two different F-P cavity distances ($\Delta\lambda$=3.98 pm). ω = 10Hz and ΔV = 65 mV

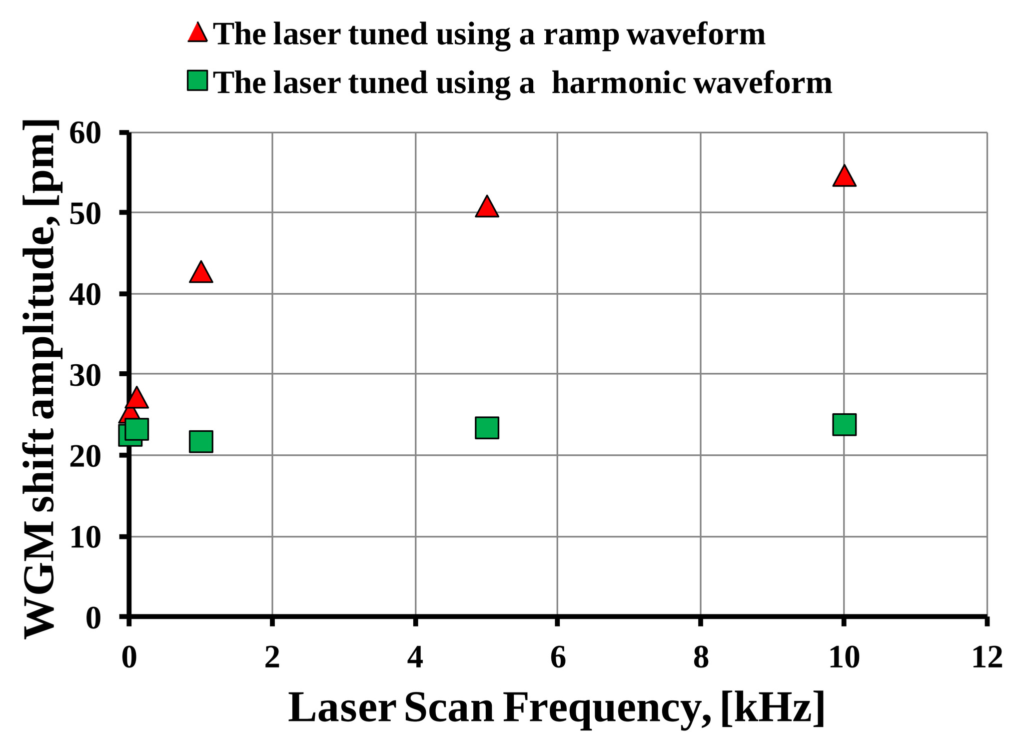
The results presented in the figures below agree with the analytical prediction of Eq. (4). Larger scanning amplitudes, ΔV, (causing larger $\dot{Q}$) lead to larger laser frequency shifts, $\Delta\lambda$. Also, larger scan frequencies, ω, result in smaller $\Delta\lambda$ and larger phase shifts. It is observed that by 20 kHz, the phase shift has nearly reached the asymptotic value of $-\pi/2$. These results show that the laser tuning is adequately captured by the simple thermal model.



Calibration curves for laser output; a) Response of the laser under different scan frequencies and amplitudes, b) Phase shift at different scan frequencies

7. Experimental results

The figure below shows the WGM shift amplitudes observed in the force experiment for both linear (using ramp waveform) and harmonic (using sine waveform) .



WGM shift dependency on laser scan frequency

8. Conclusions

The thermal inertia of the laser at high scanning frequencies impedes with the proper tuning of the laser inducing measurement errors. The results show that harmonic tuning of the laser allows for proper calibration and mitigates measurement errors. We demonstrate dynamic force measurements up to 10 kHz using this approach. A simple lumped-heat capacity thermal model accurately predicts the laser's tuning behavior.

References

[1] Ayaz, U.K.; Ioppolo, T.; Ötügen M.V. , "Wall shear stress sensor based on the optical resonances of dielectric microspheres , " Meas. Sci. Technol. Vol 20,(2011).

[2] Ali, A. R.; Ioppolo, T.; Ötügen, V.; Christensen, M.; MacFarlane, D. , "Photonic electric field sensor based on polymeric microspheres, " J. Polym. Sci. B Polym. Phys., 52, 276–279 (2014).